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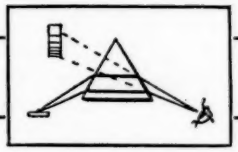

DECEMBER
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CONTENTS

Robert Williams Wood, Ives Medallist for 1933 413

Interference Scheme for Measuring the Cell Depth of a Siedentopf Ultramicroscopic Counting Chamber . . D. L. GAMBLE AND A. H. PFUND 416

Neutral Value Scales. II. A Comparison of Results and Equations Describing Value Scales . . . . . I. H. GODLOVE 419

Transmission of Ultraviolet Radiation by Water . . CHARLES D. HODGMAN 426

Improving Underwater Vision of Lifeguards and Naked Divers . . . . . ROBERT E. CORNISH 430

Index to Volume 23 431

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Journal of the
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of AMERICA

VOLUME 23 DECEMBER, 1933 NUMBER 12

Robert Williams Wood

IVES MEDALLIST OF THE OPTICAL SOCIETY OF AMERICA FOR 1933

THE Frederic Ives medal for the year 1933 has been conferred upon Robert Williams Wood.

The history of Wood's appointments may be told in few words, for he has occupied the chair of Experimental Physics at The Johns Hopkins University ever since 1901, when at the early age of thirty-three he succeeded its first incumbent, the illustrious Rowland. Before that he had spent four years on the staff of the University of Wisconsin, and earlier there had been years of study at Berlin, Chicago, Johns Hopkins and Harvard. Some of his recent work has been done at the Loomis Laboratory; often during his career, papers signed jointly by him and foreign physicists have testified to periods of research in several countries of Europe; and the esteem in which he is held abroad is attested by the fact that he is one of the few Americans who are Foreign Members of the Royal Society.

Of Wood's work outside of the field of light some mention should be made, though it is not included in the scope of the Ives Medal. It comprises papers of his student years on the dissociation of electrolytes and on the temperature prevailing in the glow-discharge; an important series of studies of the condensation (or alternatively the reflection) of molecules of vapor impinging upon surfaces of metal; another group of researches on supersonic waves of great frequency and extraordinary intensity generated in liquids by piezoelectric oscillators; and many interesting observations on the combination of hydrogen atoms into molecules.

It is however as a great authority on light that Wood is known universally. Few indeed are the phenomena of light which he has not examined and helped to clarify! He has touched upon almost every subdivision of optics, and one may say of him as Johnson of Goldsmith, *nullum quod tetigit non ornavit.* The ultraviolet as high as eight hundred and thirty Angstroms, the infrared as deep as two hundred microns, are as familiar to him as the visible spectrum.

In the wide diversity of Wood's researches, there are half a dozen at least among which it would be hard, or better said impossible, to choose the most important. It is not necessary to attempt a choice; but since the preeminence of first mention must perforce be accorded to some one thing, let it be the great sequence of Wood's studies of the fluorescence of gases, evoked by light of frequencies rigidly controlled and identical with natural frequencies of the illuminated gas, and to which he gave the general name of "resonance radiation." As early as 1905 he was observing the fluorescence spectrum of sodium vapor, and the trains of lines almost equally spaced in wave-length and replaced by other trains of lines so soon as the exciting frequency was changed by only a little. He extended these observations greatly in studies of sodium and other vapors, and thus helped to lay a broad foundation for the quantum-

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mechanical theory of molecular spectra (these fluorescence-spectra being due to diatomic molecules) which was not to be born for ten years after his first observations.

In other famous cases also Wood has provided the data on which future theories were destined to be built. His is one of the few names cited in Bohr's paper of July, 1913, with which modern atomic theory commences, for he had observed the continuum extending beyond the head of the principal series of the (atomic) spectrum of sodium, which fits well with Bohr's theory because it may be ascribed to the extraction of electrons from sodium atoms by the incident light. There was also his extensive work on the "quenching of fluorescence"—the fact, that is to say, that when a fluorescing vapor is mingled with another gas (or even a large extra quantity of itself) its fluorescence is enfeebled or altered in appearance or extinguished altogether; the many examples of this fact are now interpreted as instances of "collisions of the second kind," in which the energy which a molecule of the former vapor has received and would otherwise reradiate as light of fluorescence is transferred in part or in whole to a molecule of the other kind, or undergoes some other change at the moment of a collision. Much later, he with Ellett discovered the powerful effect of weak magnetic fields on resonance-radiation; this evoked a score at least of papers from some of the leading theorists of our time, and scores upon scores of further experiments of which the end is not yet. It must not however be thought that all of Wood's investigations have preceded the theories which serve to interpret them. Various of his papers describe experimental tests of the quantum theory of emission and absorption of light, and of collisions of the second kind; there is, for instance, his study of the intensities of various lines of the fluorescence spectrum of mercury atoms excited by white light, in which he verifies the prediction that these should increase as the first, second, or third powers of the intensity of the exciting light according as the initial states of the transitions which produce them are reached by one, two, or three consecutive transitions from the normal state of the mercury atom, entailing one, two or three successive absorptions of incident photons.

Another notable group of researches, begun in 1928, bears on the scattering of light with change of frequency, which is associated with an excitation of the molecule which scatters—the Raman effect. Within a few months of Raman's announcement of his discovery, Wood was obtaining new data in profusion, with experimental devices capable of stimulating the effect with unprecedented strength. Everyone recognized this as characteristic of him; indeed, the term "a Wood experiment" has come to be employed of any which is distinguished by unusual ingenuity and efficacy, and especially when it is made by simple means. Take as an example an experiment of thirty years ago, on the dispersion of sodium vapor. Wood takes a tube of helium as source of light; applies to it a magnetic field which splits the D_3 line into a Zeeman triplet, of which the extreme components are a quarter of an Angstrom unit apart, at 5874.87 and 5875.13; removes the intermediate component of the triplet by a nicol prism; sends the remaining lines through the vapor occupying one limb of an interferometer, and from the visibility-curves of the apparent fringe-system which is really the superposition of the fringe-systems of these two lines, he determines the ratio of the refractive indices corresponding to their wave-lengths.

Wood's work abounds in such experiments. There is the paraboloidal mirror brought into being (one can hardly say "constructed") by the simple scheme of spinning a bowlful of mercury. There is the irradiation of sodium vapor by one alone of the D-lines, totally separated from the other. There is the careful adjustment of conditions in luminous discharges, until twenty or twenty-one lines of the Balmer series of hydrogen appear in place of the three or four which were all that had previously been excited in the laboratory, and no fewer than fifty-eight lines of the principal series of sodium instead of only seven! There is the study of the light of wave-length 2537 re-radiated from mercury vapor when light of equal wave-length falls upon it, as the density of the vapor is gradually increased until the re-radiation assumes the character of metallic reflection. There is the study of the peculiar capability for fluorescing which mercury vapor exhibits when rapidly distilling from liquid mercury, and which eventually was shown to be due not to any peculiar quality of the vapor

molecules fresh from the liquid, but to the incidental fact that all foreign gases had been pushed away from the scene by the rapidly-moving vapor torrent. There are numberless brief items in Wood's famous textbook of *Physical Optics*. It would be impossible to mention all of them in any reasonable space; but it would be inexcusable to fail to emphasize Wood's work on the diffraction grating.

The ruling of good gratings is an art; and those who have achieved success in it are fewer far than those who have attained to eminence in music or in painting, during the brief period of little over a century since Fraunhofer introduced it. In taking it up Wood was following the traditions of his chair, for in this art Rowland was the first in America and one of the greatest in the world. No one but a practicing spectroscopist could give a just assessment of Wood's gratings; but not even the most casual traveller among laboratories could fail to note that those which have them are envied, and not even the most casual listener at a meeting of the Physical Society can fail to be impressed, when he hears of a new grating of which practically all the light is concentrated in a single order, on a single side of the incident beam!

To speak of some procedure as an "art" gives the impression that the master thereof cannot explain the underlying principles of his success. To some degree this is still true in the art of the ruling of gratings; but Wood has done his best to limit the realm of the unforeseeable and the inexplicable. Gratings suitable for the visible spectrum have grooves so narrow that the microscope cannot reveal their shape. Wood makes gratings with grooves broad and deep enough to be examined, and uses them in the infrared, so that both the profile of the grating and the quality of its diffraction-spectrum are observable! In reading any article of Wood's, one is tempted again and again to quote phrase after phrase; and in one of his articles upon these "echelettes" as he has called them, occurs a passage eminently quotable, which I will reproduce in part, as it is fitting that in such a place as this the medalist himself should speak. It is not fully typical (what single passage could be?) but it will serve to illustrate two aspects of Wood on which I have not touched: his vivacious and fluent style, and his delight and skill in the actual manipulations of matter on which experimental physics is ultimately based.

". . . After considerable experimenting with various metals and ruling points, I came to the conclusion that soft alloys must be avoided, for it appeared to be impossible to cut a groove with optically flat sides. . . . The method finally adopted was the following: a sheet of polished copper plate, such as is used by photo-engravers, was gold-plated and polished. The plates were found sufficiently flat for the purpose and had a much better optical surface than anything that I was enabled to produce on a copper plate by grinding and polishing, for the final polishing always produced irregular undulations . . . and I was unable to get any suggestions from professional opticians accustomed to the polishing of glass and speculum metal. If anyone has worked out a method of getting a flat optical surface on such metals as copper or gold, I shall be very glad to hear of it, as it will doubtless improve the quality of the gratings. . . . The copper plate was varnished with asphalt on the back to save gold, and gilded in as large pieces as the gilding establishment could handle. These large sheets were then cut up to the required size with a circular saw. It is important to instruct the gilder to do as little buffing as possible. My first plates were spoiled by having too thick a deposit of gold and too vigorous buffing or burnishing. The best treatment is the one which they give to the thinnest coats, which would be completely removed if polished by the methods employed for thicker deposits. If a thick deposit is given and polished in the usual way, the optical surface is ruined by the formation of undulations, though it is hard to convince the gilder that it is unsatisfactory. I mention these details for the benefit of others undertaking the manufacture of these gratings, for it took me nearly a week to convince the gilder that he could be taught anything about the nature of metals and how they should be treated. . . . The circumstance that the first plate which I placed in the hands of the plater flew into three pieces as soon as he put it in the hot alkaline solution which they use for cleaning thin metal work, convinced him that there was something about metals to be learned, and he was more willing to take advice thereafter."

K. K. D.

An Interference Scheme for Measuring the Cell Depth of a Siedentopf Ultramicroscopic Counting Chamber

D. L. GAMBLE* AND A. H. PFUND**

(Received October 17, 1933)

IN determining the particle sizes of materials lying close to or beyond the true limit of resolution of the ordinary microscope, the ultramicroscopic count method of Zsigmondy has frequently been used. In employing this method, Gehman and Morris[1] have developed a technique which takes advantage of the high degree of dispersion which can be obtained with certain pigments by milling them in rubber. A suitable quantity of the uniform rubber-pigment mix thus obtained is dissolved in xylene and the pigment concentration of this suspension adjusted by further dilution with Nujol. This technique has added greatly to the value of the count method as a means of determining the particle sizes of ultramicroscopic pigments.

The Zsigmondy method consists primarily of determining, by ultramicroscopic count, the number of particles contained in a definite volume of a suitable suspension of the material of known concentration. From these data, an average particle size diameter may be calculated. An ultramicroscope, consisting of a cardioid dark ground condenser, a fused quartz Siedentopf counting chamber, and a suitable objective and ocular, is used in this work. The counting chamber and holder are shown in Fig. 1. The chamber consists of two quartz disks, the lower one having a cylindrical depression in the center which forms the cell. The depth of this cell is of the order of magnitude of ten microns. The counting chamber is filled with a dilute suspension of the material to be measured, and the average number of particles existing in a definite volume is determined, microscopically. This volume is determined by the depth of the cell and the area viewed, which is defined by an Ehrlich stop inserted in the ocular.

Since it is practically impossible to fill and assemble the counting chamber in such a way as to have always the same cell depth, it is highly desirable to have an accurate method of measuring this depth after the cell has been loaded and assembled, ready for counting. An interference phenomenon known as the channeled spectrum is nicely suited to this purpose.

FIG. 1. Siedentopf counting chamber.

It has the advantages over the ordinary interference methods of ease of manipulation and in not requiring monochromatic light. This particular interference phenomenon is not so well-known, probably because it is described in relatively few textbooks on optics.[2, 3] For this reason, a description of its adaptation to this purpose was considered worth while.

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[1] S. D. Gehman and T. C. Morris, *Measurement of Average Particle Size of Fine Pigments*, Ind. and Eng. Chem., Anal. Ed. p. 157, April 15, 1932.

[2] Fizeau and Foucault, Ann. de Chemie et de Physique, Third Series **26**, 138 (1849).

[3] Wood, *Physical Optics*, p. 157.

The phenomenon to be observed in making a determination of the cell depth is the result of interference occurring between light rays multiply reflected from the inner surfaces of the two quartz disks which define the thickness of the cell. Since the medium which fills the cell is very close in refractive index to that of the quartz, it is necessary to increase the reflecting power of these interfaces. This is done by sputtering thin films of platinum on the inner surfaces of the disks. These films are sputtered on in the usual way, the disk being so masked that only a film approximately 3 mm square is allowed to form at the center, as shown in Fig. 1. The metallic films are made thin enough to transmit freely but sufficiently thick to give the desired improvement in reflecting power. The thickness of such a film is infinitesimal as compared with the depth of the cell. The adherence of these metallic films may be greatly improved, if, after sputtering, the disks are held for a few minutes in a Bunsen flame. After this treatment a cell may be used and cleaned a great number of times before it becomes necessary to resputter.

The optical set-up required for the determination of the cell depth is shown diagrammatically in Fig. 2. The cell, C, loaded and ready

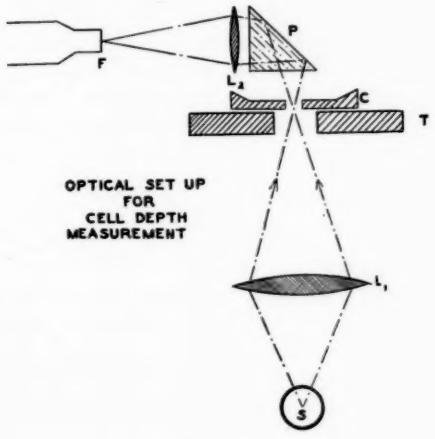

FIG. 2.

for counting, is placed on a horizontal stage, T, having a central hole through which a beam of light may be directed. An image of the light source, S, a tungsten filament lamp, is focussed at the center of the cell by means of a relatively long focus lens, L_1. In turn, an image of the cell is focussed on the slit, F, of a spectrometer by means of a total reflection prism, P, and a short focus lens, L_2. The multiple reflections which occur between the inner faces of the cell set up conditions of destructive interference which will occur at definite wave-length intervals throughout the spectrum, depending upon the degree of separation of the surfaces. The continuous spectrum observed in the spectrometer will be channeled with a series of interference fringes (Fig. 3). If then the number of these fringes,

FIG. 3. Channeled spectrum corresponding to a cell depth of approximately 6 microns (cell filled with air).

lying within a known wave-length interval, is determined, the depth of the counting cell may be calculated from the following equation:

$$t = N\lambda_1\lambda_2/[2\mu \cos r(\lambda_2 - \lambda_1)]$$

where t = thickness of cell
N = number of fringes in wave-length interval, $\lambda_1 - \lambda_2$
μ = index of refraction of medium filling the cell
r = angle of incidence of light ray on cell = 0 (approx.)
$\cos r = 1$ (small angle of incidence)
λ_1 = short wave-length limit of interval
λ_2 = long wave-length limit of interval.

It has been found convenient to use a wave-length spectroscope in this set-up. This does away with the necessity of a reference spectrum and permits the counting of a whole number of fringes and the determination of the corresponding wave-length interval from the calibrated wave-length drum. However, an ordinary spectrometer can be employed using a superimposed line spectrum,[4] such as that of the mercury arc or helium discharge tube, to furnish the reference lines.

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[4] D. L. Gamble and A. H. Pfund, Ind. and Eng. Chem., Anal. Ed. 2, 63 (1930).

When the cell depth for this central region has been determined, the ultramicroscopic counting is carried out at positions along the edges of the sputtered area of the cell. In doing this, the assumption is made that over the area employed in making the thickness determination and particle counts the cell depth does not vary appreciably. The correctness of this assumption has been tested for the cells used in this laboratory and the cell depth over the central area employed was found to be essentially constant. However, it would probably be necessary to test each individual cell. This can be done by merely sputtering the entire area of the cell and measuring its depth at different positions employing the channeled spectrum as described above.

By using the Gehman and Morris dispersing technique and employing the channeled spectrum as a means of determining cell depth, surprisingly good reproducibility has been obtained in the measurement of the particle sizes of fine zinc oxides.

Acknowledgment

The authors wish to acknowledge the assistance of Mr. Tracey Steele and Mr. Clyde Hall.

Neutral Value[1] Scales. II. A Comparison of Results and Equations Describing Value Scales

I. H. GODLOVE, *Munsell Research Laboratory, Baltimore, Maryland*

(Received June 29, 1933)

I. INTRODUCTION

THERE are three general types of psychophysical functions of interest to workers in colorimetry (Troland[2]). Although the practical application of colorimetric science is built largely upon relations of Troland's type (2), the formulation of relations of the direct type (1) is of the utmost importance in the ultimate development of the science itself, as well as in applied colorimetry. On certain assumptions, relations of a third type (Troland's footnote) can be integrated to yield relations of type (1). A more direct method of setting up psychophysical scales, free from assumptions, consists in the production by trial and error of a very large number of color standards and a choice of these such that there is evoked in the average normal observer, under standard conditions and a specified state of adaptation of his visual mechanism, colors each of which differs from its immediate neighbors by constant differences of brilliance, hue and saturation. We then determine the physical stimulus variables corresponding to each color, and by regarding the three attributes of color as the color variables, we can plot the relations between the stimulus and the color variables. A great amount of such work has been done in this laboratory. A simple case of such true psychophysical scales is the value scale for neutral colors described in the first paper of this series,[1] since here hue and saturation do not enter, and we have a univariant system; the members of the scale differ from each other only in brilliance (value).

The agreement of the results by a "value-step method" (Troland's direct type 1) and a "just-noticeable-difference method" (the type of Troland's footnote) was reported.[1] The reported results, and certain supplementary ones not yet reported, confirm the conclusion of Cobb[3] that, of the various conditions which affect the relation between value and reflection, the one of greatest practical importance is the reflection of the background against which the value scale is viewed; while the general level of intensity of illumination of the sample and background, within the limits of ordinary indoor illumination, and a quality variation from that of "white light" to that of artificial (tungsten lamp) illumination, have no great effect on the results. It is now proposed to examine the various expressions which have been suggested for the relation of value and energy stimulus, to find which of these (or of new ones) best fits the Munsell data as well as the data of Cobb,[3] to suggest the mathematical bases of these equations, and to compare the results of the two investigations.

As a starting point, it may be regarded as an experimental fact that value is a function of the reflecting properties of the surfaces used as the stimuli and of the background to which the visual mechanism is adapted, and is not a function of the intensity of illumination, within a moderate range of intensities.[4] If we describe the proportionate changes of the stimuli from R_1 to R_1' and from R_2 to R_2', as the illumination is changed by the factor K, and of the stimulus R_m, which evokes the value "midway" between

[1] The relation between *value* and *brilliance* is given in the first paper of this series, note 1. See Munsell, Sloan and Godlove, J. Opt. Soc. Am. **23**, 394 (1933).

[2] L. T. Troland *et al.*, Report of the Colorimetry Committee of the Opt. Soc. of Am., 1920–21; J. Opt. Soc. Am. and R. S. I. **6**, 539 (with footnote) (1922).

[3] Cobb, 1913 to 1916. See reference 20 of the first paper.

[4] See Kohlrausch; Tagessehen, Dämmersehen, Adaptation, I. Allgemeines über Umstimmung und "Farbenkonstanz der Sehdinge," in Handb. d. normalen u. pathologischen Physiol. **12**, 2nd half, Receptionsorgane, II, p. 1502; Berlin (1931).

R_1 and R_2, to R_m' by the equations

$$R_1'/R_1 = R_m'/R_m = R_2'/R_2 = K, \qquad (1)$$

then we may make certain simple hypotheses as to the changes in sensation. The first hypothesis is that an observer chooses a stimulus such that the mid-value of the sensation between S_1 and S_2 is the *arithmetic mean* of these; i.e., that there are equal differences of value between the mean and the other two sensations, or both

$$\begin{aligned} S_2 - S_m &= S_m - S_1 = d, \\ S_2 = S_m &= S_m - S_1 = d', \end{aligned} \qquad (2)$$

where d and d' are constants. It may readily be shown that the necessary and sufficient condition to satisfy these equations is that

$$S = F(R) = c \log R + k, \qquad (3)$$

which is therefore the solution resulting from the arithmetic mean hypothesis. This is the well known Weber-Fechner law. If on the other hand an observer chooses a stimulus such that the mid-value of the sensation between S_1 and S_2 is the geometric mean of these, then the relation between value and stimulus which results is the Plateau exponential law

$$S = F(R) = kR^c, \qquad (4)$$

where k and c are constants. Delboeuf[5] pointed out that according to the Weber-Fechner law, a small positive value of R corresponds to a negative value of S, and zero value of R to an infinitely negative value of S, which is an absurdity. Further his experimental results were not entirely independent of the illumination, as required by the Weber-Fechner law. He accordingly modified the latter to the form

$$S = c \log [(R+k)/k], \qquad (5)$$

where k and c are constants. Although Plateau retracted his own law in favor of Delboeuf's, and Lehman[6] and Neiglick[6] approximately confirmed the latter, Breton[6] obtained results which could be best expressed by the Plateau law with the exponent $c = 0.5$; and Merkel[6] and others obtained experimental results which it was pointed out by Stefanini[6] corresponded to a position *intermediate* between the logarithmic and exponential laws.

None of the foregoing equations contain an important variable, the reflectance of the background. Adams and Cobb's[7] equation (Eq. (6)), which does contain this, was derived on the basis of the Lucas "All-or-none hypothesis" and other assumptions. It may be noted that Eq. (3) should give a straight line when S is plotted against log R, and Eq. (4) when log S is plotted against log R; while the Adams and Cobb equation can be rearranged to show that when $1/S$ is plotted against $1/R$, a straight line is obtained. The latter equation is

$$S = cR/(R+R_a), \qquad (6)$$

where S is the sensation measured from a point of reference S_0, c is a constant, R is the test field brightness, and R_a is the adaptation-brightness.

For comparison with the published[1] results of the present J. N. D. investigation (from which the results of the value-step method differ only very slightly), a value scale has been computed from Cobb's determinations of the J. N. D. in value at various value levels. The series of brightnesses required to form ten equal intervals of sensation between 0 ml and 24.5 ml were calculated by the graphical method described in the first paper of this series. The data in millilamberts were then converted into reflection units by assuming that the brightnesses were obtained from reflecting surfaces illuminated by 22.8 f.c. of light as follows: Since the brightness of the surrounding field used by Cobb was 5.5 ml (and it was found that the effect of moderate changes in illumination was small), it may be considered as a surface of 22.45 percent reflectance illuminated by 22.8 f.c. of light. The data given in the first row (labelled *Reflectances* R_C) of Table I are therefore the series of reflectances required between the limits of 0 and 100 percent to form a scale of 10 equal intervals of value when viewed on a background of 22.45 percent reflectance. The seventh row (labelled *Reflectances* R_M) of the same table gives the

[5] Delboeuf, Bull. de l'Acad. royale de Belgique **34**, 250, 261 (1872).

[6] See the discussion of these laws in the historical section of the first paper of this series (reference 1) and references 12 to 18 of that paper.

[7] Adams and Cobb, J. Exper. Psychol. **5**, 39–45 (1922).

TABLE I. *Experimental and computed value.*

Equations are made to agree with experiment at values 5 and 10;* also, the form of all makes them fit at value 0.

					Cobb Data					
Reflectances R_C	0	2.30	5.01	8.48	12.9	18.5	25.4	34.1	46.3	67.5	100.0
					Values						
Cobb (exp.)	0	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Adams and Cobb*	0	1.03	2.02	3.03	4.04	5.00	5.88	6.67	7.45	8.31	9.04
Modified Adams and Cobb	0	0.94	1.89	2.90	3.95	5.00	6.00	6.95	7.92	9.02	10.00
Delboeuf	0	1.19	2.20	3.17	4.10	5.00	5.85	6.69	7.60	8.76	10.00
Plateau-Munsell	0	2.12	2.92	3.63	4.31	5.00	5.70	6.43	7.29	8.51	10.00
					Munsell Data						
Reflectances R_M	0	1.12	2.90	5.95	11.05	18.0	27.3	38.9	53.6	72.8	100.0
					Values						
Munsell R. L. (exp.)	0	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Adams and Cobb*	0	0.57	1.36	2.45	3.78	5.00	6.06	6.91	7.60	8.16	8.65
Modified Adams and Cobb	0	0.49	1.20	2.24	3.59	5.00	6.31	7.44	8.40	9.24	10.00
Delboeuf	0	0.66	1.49	2.56	3.82	5.00	6.12	7.13	8.08	9.01	10.00
Plateau-Munsell	0	1.63	2.39	3.20	4.11	5.00	5.92	6.83	7.77	8.80	10.00
New empirical "background equation"	0	1.28	2.06	2.93	3.96	5.00	6.06	7.08	8.09	9.07	10.00

* The Adams and Cobb equations were fitted to experiment only at value 5, since one constant is the reflectance of the background.

average value scale of the present J. N. D. experiments.

A comparison of the two sets of data shows that at low levels *Cobb's observers required higher reflectances and at high value levels lower reflectances* than did the observers of the present investigation, the agreement being good at middle (5) value. In order to find an explanation of the differences in the results obtained we shall compare briefly the experimental conditions of the two investigations. (1) Cobb's determinations were made with a background only slightly lighter than that used in the present investigation (i.e., 22.4 percent as compared with 19.1 percent, the latter being checked by the value-step experiments with a 21.6 percent reflecting background), so that the differences cannot be attributed to this factor. (2) Although Cobb's determinations were made with yellowish artificial light and those of the present investigation with neutral light, the results of experiments in this laboratory indicate that this factor is of minor importance. (3) The test surface in Cobb's experiments was a rectangular field whose sides subtended visual angles of 2.6° and 2.0°, respectively, whereas the test surface used in this investigation was a circular field whose diameter subtended a visual angle of 4°. Preliminary unpublished investigations of our own indicate that this difference in size of field would have no appreciable effect on the results. On the other hand, the existence of a dividing line in the field in the one case and not in the other is a possible source of difference in the results. (4) The just-noticeable-difference unit employed by Cobb was based upon "finding the point on the stimulus scale such that the sums of the "wrong" judgments on either side were equal."[8] In the

[8] In Cobb's observations the stimuli were presented in random order, as is customary in the "method of right and wrong cases." The ordinary method of calculation employed in this method could not be used because (1) the stimuli were changed during the course of the work, and (2) the number of experiments with each stimulus was not sufficient. The method of computing the J. N. D. was based on the table of Fechner, in turn founded on the Gauss law of error, and consisted in "finding the point on the stimulus scale such that the sums of the wrong judgments on either side are equal." Certain approximations were made, but the computation was intended to be such that the probability of seeing the difference "correctly" at the threshold was 0.50, and the threshold was taken as the point where the sums for the cases of appearance of greater brightness on the left half of the field were equal to the corresponding cases for the right half plus cases of appearance of equality (the equal-stimulus cases being actually only 4 percent of the total). The method used, Cobb says "is based on the same assumptions as the classical method of constant stimuli." The J. N. D. obtained by the method described

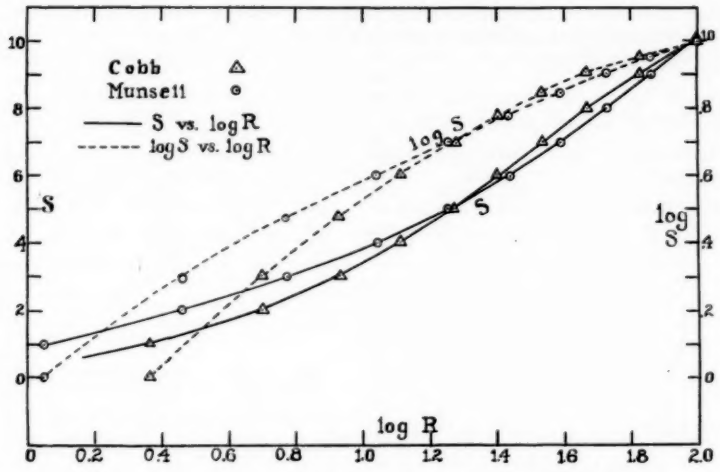

FIG. 1. Comparison of experimental data with Eqs. (3) and (4).

present investigation the difference in brightness was decreased (or increased) gradually in order to ascertain the smallest difference which the observer could perceive *with certainty*. Since the method of determining the just noticeable difference which was used in the present investigation has been shown to give results in agreement with those obtained by the value-step method, the just noticeable difference when determined by this procedure can be accepted as a unit of sensation. It is possible therefore, that the difference in the value scales obtained from Cobb's data and from the present investigation are due to the fact that the J. N. D. as determined by Cobb cannot with equal validity be treated as directly proportional to the sensation unit of the value-step method. (5) In the present investigation the average value scale was obtained from the results of six observers (by the J. N. D. method; more by the other). This number of observers may be considered sufficient to determine an average value scale because of the almost exact agreement with that obtained in the independent investigation by a different method by four of the same observers and 12 additional observers. In Cobb's investigations, however, there were only three observers. Cobb's average lies entirely *without the extremes* for our six observers at the first to third and sixth to ninth value steps[9] (see Fig. 10 of the first paper of this series[1]). It is possible, therefore, that the difference in the results obtained by Cobb and by this laboratory are partly due to individual differences in sensitivity in the two groups of observers. Two, or perhaps three, *possible reasons* have thus been found for the differences in the results obtained in these two investigations. Further research would be required in order to decide which of these is the more probable explanation of the differences.

II. Comparison of Calculated and Observed Data

Fig. 1 shows S (solid line) and $\log S$ (broken line) plotted against $\log R$, for both sets of J. N. D. data. It is seen that neither gives a straight line, as they should if Eqs. (3) and (4) were valid. Since one is concave and the other convex downward it is probable that the expression which best fits the experimental data (for backgrounds of 18 to 20 percent reflectance) is one which is intermediate in character between Eq. (3) and Eq. (4). Fig. 2 shows $1/S$ plotted against $1/R$. Here it is seen that a straight line is obtained for the Cobb but not for the Munsell data.

would of course be smaller than that obtained by the method of the present investigation; and it is seen that this is actually the case by comparing the results.

[9] The data by the second method throw less light on this question, since the value scale determined by it was made to agree with the J. N. D. scale at values 2.12 and 9.55.

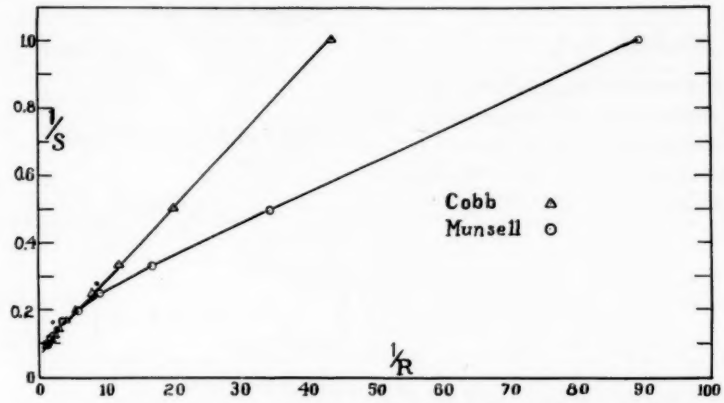

FIG. 2. Comparison of experimental data with the Adams and Cobb equation (Eq. (6)).

The Adams and Cobb formula (Eq. (6)) is a step in advance, in taking account of the adaptation-brightness, which for the present purposes may be taken as the reflectance of the background. The other equations, ((3), (4), (5)) cannot be expected to hold exactly under experimental conditions such that the light reflected from the background is equal to a constant fraction of the illumination, for then the brightness of the background, to which the eye is adapted, is variable. The experimental conditions implied in the equations would be realized if the reflection of the background were zero or were always maintained inversely proportional to the illumination, so as to keep its brightness constant.

In spite of the difficulty just mentioned, it is of interest to compare the sensation scales computed from Cobb's and from the Munsell experimental data with the various equations named, and with certain new ones. It is clear from the form of the equations (except Eq. (3) as already noted) that zero stimulus gives zero sensation. Since the equations contain two constants, it is possible to make the computed data agree exactly with the experimental at two points. These were at the value steps 5 and 10, thus giving agreement at the middle (where the Cobb and the Munsell experimental data agreed very well) and at the two ends.[10] Comparison with the Delboeuf modification of the Weber-Fechner law is included; also with the special case of the Plateau law having the exponent 0.5 proposed by Breton and used by Stefanini and A. H. Munsell.[11] In addition to the Delboeuf, Plateau-Munsell, and Adams and Cobb equations, other (empirical) equations were tried. Some of these were: a modified Adams and Cobb equation, an empirical two-arbitrary-constant of the Adams and Cobb form, a three-arbitrary-constant equation for use as an interpolation formula of a form intermediate between the types of the Delboeuf and Plateau equations, and a new empirical "background equation," having only *one* arbitrary constant. The last-named equation not only fits the Munsell data for a *gray* background (reflecting 19.1 percent), but also about equally well fits unpublished Munsell data for a *white* background (reflecting about 60 percent), even though the arbitrary constant is determined to fit the experimental data at value 5 for the gray background. The general form of this equaton is

$$V^2 = (1 - 100b)R - bR^2, \qquad (7)$$

[10] The more accurate but more tedious least squares determination of the constants was not thought worth while in view of the limitation of the value of such formulae in expressing the experimental data for all backgrounds, and because of the desire to fit the equations to the experimental data exactly at value 5, since here the Cobb data agreed very well with the Munsell J. N. D. data (and better with the Munsell value-step data). The Adams and Cobb equation in its unmodified form could not be fit at two points—the fit at value 10 was not made—since it contains only one arbitrary constant, the other being the reflectance of the background.

[11] See notes 5, 6, and 22 of the first paper of this series.

where

$$b=c(10-R_B^{\frac{1}{2}}), \tag{8}$$

R_B is the reflectance of the background, and c is a constant determined for all backgrounds by fitting to the experimental data at value 5 for a gray background of $R_B=19.1$. For a 100 percent reflecting background this equation reduces to the form

$$V^2=R \tag{9}$$

and for other particular backgrounds to the simple form

$$V^2=mR+nR^2, \tag{10}$$

which can be very readily used with the aid of a table of squares. The results of fitting these equations to the experimental data of Cobb and of the Munsell Research Laboratory at the values 5 and 10 (except as already noted) for the gray backgrounds follow. In these equations V is the value on a ten-step value scale, and R is the percentage reflectance. The equations for the *Cobb* data are:

Adams and Cobb

$$V=\frac{11.068R}{R+22.45}, \tag{11}$$

modified Adams and Cobb

$$V=12.937\left(\frac{R}{R+29.366}\right), \tag{12}$$

Delboeuf

$$V=7.7641\log\left(\frac{R+5.4325}{5.4325}\right), \tag{13}$$

Plateau-Munsell

$$V=1.5081R^{0.41078}, \tag{14}$$

and for the *Munsell* data:

Adams and Cobb

$$V=\frac{10.306R}{R+19.1}, \tag{15}$$

modified Adams and Cobb

$$V=12.812\left(\frac{R}{R+28.124}\right), \tag{16}$$

Delboeuf

$$V=7.5925\log\left(\frac{R+5.0625}{5.0625}\right), \tag{17}$$

Plateau-Munsell

$$V=1.5545R^{0.40421}, \tag{18}$$

new empirical "background Eq."

$$V^2=1.4743R-0.004743R^2. \tag{19}$$

In Table I, experimental and computed values are given for comparison, and in Fig. 3 is shown the Munsell experimental value scale (solid line) and values computed from the different equations. It should be noted that some of the fits (e.g., of the Adams and Cobb equation) for the whole range of values *might* be better if the arbitrary constants were adjusted to fit at some point other than value 5. In Table II are given the differences between observed and computed results, in value steps, grouped into two groups (dark and light steps, respectively). From the tables it is apparent, as partially shown by the graphs, that none of the equations except the new empirical "background equation" fits the experimental data (except also that the Adams and Cobb equation fits the Cobb data very well for low values, and the modified Adams and Cobb equation fits the Cobb data well—but

TABLE II. *Deviations of computed from experimental values.*

(Here plus means the computed values are greater than the experimental, minus the reverse; plus or minus means "crossing over" in the range involved.)

	Cobb			Munsell R. L.			Average of Both		
	Low	High	All	Low	High	All	Low	High	All
Adams and Cobb	+0.03	−0.42	±0.225	−0.46	±0.35	±0.405	±0.245	±0.385	±0.315
Modified Adams and Cobb	−0.08	±0.04	±0.06	−0.62	+0.35	±0.485	−0.35	±0.195	±0.27
Delboeuf	+0.165	−0.275	±0.22	−0.37	+0.085	±0.23	±0.27	±0.18	±0.22
Plateau-Munsell	+0.475	−0.52	±0.63	+0.33	−0.17	±0.25	+0.54	−0.345	±0.44
New empirical "background Eq."				±0.11	+0.075	±0.09			(0.09)

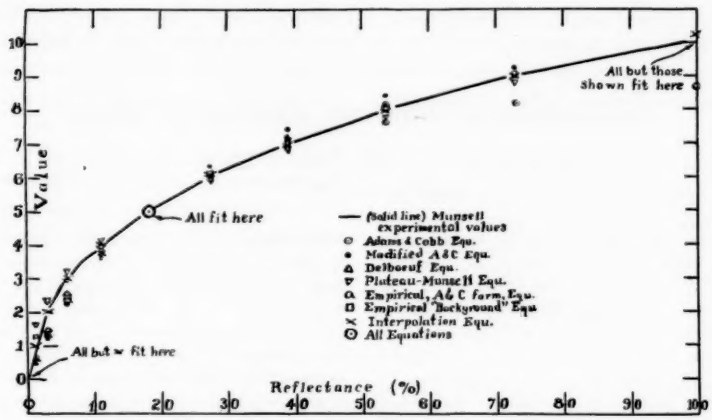

FIG. 3. Experimental (Munsell R. L.) and computed values.

both fit the Munsell data poorly). Of course the three-constant equation of the type intermediate between the Fechner-Delboeuf and Plateau laws (not shown) fits the Munsell data better than any of the other equations (average deviation 0.03).

It should be noted that the constant of the Adams and Cobb equation which gives exact fit at value 5, and is meant to be the adaptation-brightness, is actually 29.4 instead of 22.45 for the Cobb data, and 28.1 instead of 19.1 for the Munsell data. This is of course the constant obtained by forcing the curve through an arbitrarily chosen middle point. Other constants would be obtained by fitting at other points. If instead we plot the reciprocals of V and R and pass the "best" straight line through the points, we obtain 27.0 for the Cobb data, in slightly better agreement. However, for the Munsell data, if the constant R_a is computed for the successive one-step intervals of V (10 to 9, 9 to 8, etc.), it is found not to be constant but to vary from 42.3 to 4.9. The fit of the equations to the Munsell data is shown in Fig. 3.

In conclusion the writer wishes to acknowledge the help of Dr. Louise Sloan, who wrote a preliminary draft of a part of this paper, and of Dr. D. B. Judd, who read and criticized the manuscript.

III. SUMMARY

The equations which have been proposed for the relation between "value" and reflection, and the possible reasons for the differences between the experimental results of Cobb and of this laboratory bearing on this relation, have been examined. New empirical equations were also investigated. None of the previously proposed equations are in good agreement with the experimental data of this laboratory. Although the Adams and Cobb equation takes account of the reflectance of the background, the most important of the variable conditions, and fits very well the Cobb data for low values, it does not fit well the Munsell data; certain modifications of it give better agreement. A new empirical equation (Eq. (7)), *containing the reflectance of the background and only one arbitrary constant* fits the Munsell data very well for both gray and white backgrounds (even though the constant is determined to fit at the mid-gray point for the gray background), and *assumes simple forms* (Eqs. (9) and (10)) for particular backgrounds. For the experimental conditions of the work in this laboratory, the best fit to the data is given by an equation of a type intermediate between those of the Fechner-Delboeuf and Plateau-Munsell equations. Such an equation is useful as an interpolation formula.

Transmission of Ultraviolet Radiation by Water

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(Received Aug. 10, 1933)

Pure distilled water has been shown to be relatively transparent to ultraviolet radiation. Sea-water, however, has been found to be considerably less transparent. The presence of soluble mineral salts was judged to be the cause. Measurements made by the author for the fresh waters of certain lakes and streams in the vicinity of Cleveland, indicate that although obviously carrying a far smaller mineral content, they also have a relatively low transmittance. Increased transmittance was found to result from passage of the samples through a Mandler filter cone of diatomaceous earth and also from the processes of coagulation and filtration to which the water of Lake Erie is submitted before being turned into the mains of the Cleveland Water System. It is concluded that the low transmittance of the fresh water cannot be ascribed wholly to dissolved mineral salts but must in part at least be due to scattering caused by the presence of fine particles.

PURE distilled water has long been known to be relatively transparent to ultraviolet radiation. Measurements were made by Kreusler[1] who found a transmittance varying from about 0.975 for a wave-length of 300 mμ to about 0.31 at 186 mμ for a thickness of 17 mm.

Tsukamoto[2] measured the absorption for a thickness of 10 mm of distilled water for wave-lengths 186.2 mμ to 220 mμ obtaining values expressed as transmittance of 0.30 and 96.5, respectively.

Hulburt's[3] work included measurements of distilled water, tap water and sea-water from λ254 mμ to λ366 mμ. He found sea-water much less transparent than distilled water, the transmittance declining rapidly with decreasing wave-length. Measurements conducted on solutions of the salts found in sea-water indicated that the low transmittance is due mainly to the presence of calcium sulfate and magnesium chloride.

Tsukamoto,[4] investigating the transmittance of sea-water in the shorter wave-lengths (212–232 mμ) also found it to be less transparent than distilled water although his value of the transmittance at λ231.7 mμ was considerably greater than Hulburt's value at 254 mμ. Tsukamoto concluded that the reduced transmittance was due to the presence of bromides.

The fresh waters of inland lakes and streams contain relatively small quantities of inorganic salts. If the low transmittance of sea-water is due to the mineral content, natural fresh waters might be expected to be much more transparent. An investigation was undertaken to determine whether or not this was the case.

A sector photometer with quartz optical parts was employed in connection with a quartz spectrograph giving an eight inch spectrum. A source of ultraviolet radiation was placed about one meter from the slit of the spectrograph. Two quartz lenses formed two images of the source on the slit; a fixed sector rotating in front of one lens and a variable sector in front of the other. The effect of absorbing media interposed in the path of rays through the lens with the fixed sector could be balanced by adjustment of the variable sector. The sectors were driven at a speed of about 120 revolutions per minute.

By means of a quartz biprism adjusted in front of the slit two contiguous spectra were produced, one from each of the two lenses. By careful adjustment the intensity of these two spectra may be equalized when the sectors have equal apertures and the absorbing medium is not in the light path. The sample, the transmittance of which is to be measured, is placed in the path with the fixed sector and successive photographs of the spectra made with the variable sector set

[1] Kreusler, Ann. d. Physik **6**, 418 (1901).
[2] Tsukamoto, Rev. d'Optique **7**, 89 (1928).
[3] Hulburt, J. Opt. Soc. Am. **17**, 15 (1928).
[4] Tsukamoto, Comptes Rendus **184**, 221 (1927).

at regularly decreased apertures. The intensity of the two spectra will be equal for wave-lengths at which the transmission of the cell and sample contained is equal to that of the variable sector.

The method is subject to certain difficulties due to failure of the reciprocity law of photographic exposure and the effect of intermittence. Experiments by Howe[5] and others appear to have established the validity of the method for normal photographic emulsions within the middle range of exposures and for a relatively low frequency of intermittence.

A vertical arc between cored carbons of the type ordinarily used for the production of ultraviolet radiation for therapeutic purposes served as a satisfactory source. The advantages over the iron or iron-copper arc are increased steadiness and intensity and the presence in the spectrum of a continuous background of considerable intensity. Since the balance of intensity in the two spectra was very sensitive to changes in position of the source, a lens was fixed at the rear of the arc to throw its image on a ruled screen so that after careful preliminary adjustment for equality the arc might readily be maintained in the exact position during exposure. Repeated photographic measurements demonstrated the fact that the adjustment for the position of the source could be held sufficiently close to avoid appreciable error from this cause.

The sharpness of the line separating the two spectra was improved by the use of a diffusing screen of ground quartz about 15 cm in front of the source.

The water sample was contained in a cell formed from two quartz plates held apart by a U-shaped separator. The transmittance of the sample would be defined as the ratio of the intensity of radiation reaching the second inner surface of quartz to that entering from the first inner quartz surface.

In order to correct for the loss of intensity due to reflections and absorption of the cell walls the separator was removed and the two plates placed in contact with a film of the liquid sample between and the transmission again measured. The conditions were thus identical except for the thickness of the sample.

If T_c be the transmission of the cell walls with the film of water, and T_s that of the sample alone, then the measured transmission of the sample and containing cell will be,—

$$T_m = T_c \times T_s \quad \text{or} \quad T_s = T_m / T_c.$$

Several independent determinations of the transmittance of freshly distilled water demonstrated the reproducibility of results, and the general agreement with the work of earlier investigators indicated the validity of the method. A series of determinations was made for the water of Lake Erie, samples being collected on several different occasions. No marked variation for different samples was observed.

Tap water from the Cleveland Water System, originally from Lake Erie, was also investigated. Samples of water were collected from other sources including a small inland lake, two small streams and an open marsh. A sample was also prepared from freshly collected snow, presumably containing only such material as might come from the atmosphere during condensation and precipitation.

It is obvious that natural conditions offer wide variations in the quantity of solid material, in the form of relatively large particles, which is in suspension when a sample is collected. To obtain uniformity the samples were in all cases filtered through ordinary filter paper before measurement.

A typical determination included a series of preliminary photographs, to determine, and adjust if necessary, the equality of the contiguous spectra without the sample. With the sample

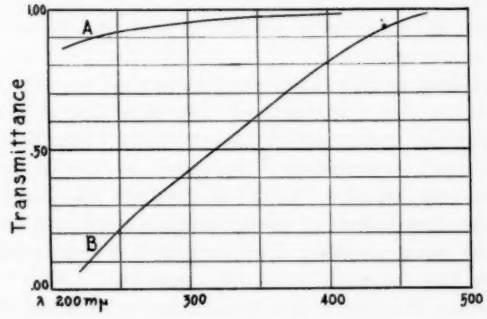

FIG. 1. Transmittance curves: *A*, distilled water; *B*, water from Lake Erie.

[5] Howe, Phys. Rev. **8**, 675 (1916).

TABLE I. *Transmittance for a thickness of 20 mm.*

λ mμ	Distilled water	Lake Erie	Tap water	Shaker Lake	Brook I	Brook II	Surface water	Melted snow
220	0.88	0.07	0.57	0.05	0.05	0.14	0.14	0.13
240	.91	.16	.90	.12	.16	.30	.25	.31
260	.93	.26	.91	.21	.25	.41	.33	.40
280	.95	.35	.91	.30	.35	.49	.39	.46
300	.96	.43	.94	.38	.45	.53	.44	.51
320	.97	.51	.96	.46	.55	.59	.54	.55
340	.98	.58	.98	.55	.63	.65	.67	.58
360	.98	.66	.99	.65	.71	.69	.72	.62
380	.98	.75	.99	.75	.80	.73	.77	.66
400	.99	.81	.99	.85	.88	.86	.82	.70

TABLE II. *Coefficient of absorption.*

λ mμ	Distilled water	Lake Erie	Tap water	Shaker Lake	Brook I	Brook II	Surface water	Melted snow
220	0.028	0.58	0.12	0.65	0.65	0.43	0.43	0.44
240	.021	.40	.023	.46	.40	.26	.30	.25
260	.016	.29	.021	.34	.30	.19	.24	.20
280	.011	.23	.021	.26	.23	.15	.20	.17
300	.009	.18	.013	.21	.17	.14	.18	.15
320	.007	.15	.009	.17	.13	.11	.13	.13
340	.004	.12	.004	.13	.10	.093	.087	.12
360	.004	.090	.002	.093	.074	.081	.071	.10
380	.004	.062	.002	.062	.048	.068	.057	.090
400	.002	.046	.002	.035	.028	.033	.043	.077

inserted a series of twelve to sixteen exposures were made of length varying from fifteen seconds to eight minutes and with decreasing sector openings.

Examination of the negatives under a magnifier served to locate the position of balance by reference to the wave-length scale which was impressed on each negative. The wave-lengths were thus indicated at which the transmission of the cell and water sample contained had the values shown by the series of sector openings. These transmission values were then corrected for the reflection and absorption of the cell and plotted to give the transmittance curve. Fig. 1 shows the transmittance curves obtained for distilled water and for water from Lake Erie. Table I gives values of the transmittance for the various samples. Table II presents the corresponding values of the absorption coefficient for the same samples. The coefficient is computed as the value of α in the equation $T=10^{-\alpha x}$ where T is the transmittance for a thickness of x cm.

The results in the case of distilled water are only slightly lower than those obtained by Kreusler in the region below 300 mμ. There is also fair agreement with the results of Hulburt in the longer wave-lengths.

The transmittance of water from Lake Erie drops from about 0.81 at 400 mμ to 0.07 at 220 mμ in a roughly linear relation. The values are considerably lower than those obtained for sea-water by Hulburt. At 280 mμ his value for sea-water reduced to the same thickness (20 mm) was 0.83 against the author's value of 0.35 for Lake Erie.

The determinations for fresh water from natural sources indicates in all cases a rather rapid drop in transparency in the shorter wave-lengths, the transmittance being in the neighborhood of .0.50 at 300 mμ and in most cases below 0.10 at 220 mμ. The contrast with distilled water, which showed transmittances of about 0.96 and 0.88, respectively, at the same wave-lengths, is marked.

The values for tap water, 0.94 and 0.57, more nearly approach those for distilled water. Since this water comes originally from Lake Erie it is evident that the cause of low transmittance is to a large extent removed by the process of coagulation and filtration to which the water of the lake is subjected before being delivered to the mains.

The results for melted snow are but slightly different from other natural sources suggesting that the cause for the low transmittance must be looked for in the materials gathered from the atmosphere during condensation and precipitation.

Further evidence along this line was obtained

TABLE III. *Increase in transmittance for 20 mm thickness due to passage through Mandler diatomaceous filter cylinder.*

λ mμ	Lake Erie	Shaker Lake	Surface water	Melted snow
220	0.33	0.11	0.13	0.11
240	.25	.18	.13	.12
260	.21	.25	.13	.15
280	.19	.29	.14	.15
300	.17	.22	.20	.15
320	.16	.13	.17	.15
340	.15	.09	.07	.14
360	.15	.07	.06	.14
380	.15	.06	.04	.13
400	.14	.05	.02	.13

by measuring the transmittance of samples before and after passage through a Mandler filter cylinder of diatomaceous earth. The increase in transmittance due to this treatment is shown in Table III and the curve for a typical case in Fig. 2.

The maximum increase is definitely in the shorter wave-lengths in the case of three of the samples. The exception is the case of the melted snow which shows a nearly uniform change.

The investigation would seem to indicate that the low transmittance of natural fresh waters cannot be attributed solely to dissolved substances but may be largely due to the presence of very small particles which stay in suspension indefinitely and are to a certain extent removed by the Mandler filter. In the case of the tap water the particles are efficiently removed by the processes of coagulation and filtration.

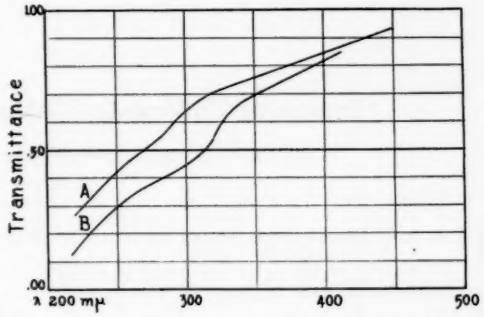

FIG. 2. Transmittance curves for a sample of surface water: *A*, after filtration through a Mandler filter; *B*, before filtration.

Improving Underwater Vision of Lifeguards and Naked Divers

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(Received October 27, 1933)

IT is well known that about two-thirds of the refraction of light in the normal human eye takes place at the surface of the cornea, only about one-third being supplied by the two surfaces of the so-called "crystalline lens." Now since the index of refraction of the aqueous humor of the eye is nearly the same as that of water, it is evident that a naked diver has lost two-thirds of the refracting power of his eyes while under water. Swimmers know that while large objects may be roughly seen while swimming under water, the vision is very indistinct. Presumably with deep diving resulting in poor light, the widening of the pupil would make vision very ineffective indeed.

This is avoided by the commercial diving dress, which has *plane* windows in front of the eyes, the cornea being immersed in air. Also goggles are on the market for naked divers, these having plane windows also, but the air space being maintained by rubber rings surrounding the glass windows, and fitting firmly to the face around the eyes. Such goggles are subject to condensation on the glass, and to leakage around the rubber, which soon greatly interfere with vision. The inside of the goggles obviously cannot be wiped out while under water, without losing the contained air, although it is indeed true that with some water inside the goggle, the diver can twist his head at intervals to swish this water over the window surface, thus somewhat improving the visibility.

However, the lack of refraction by the cornea may be considered, while under water, as a refraction error of the eye, and suitable correcting lenses designed. The author has constructed two such lenses, and finds excellent underwater vision with them, news print being read without difficulty with one of them, while without the lenses it is not even possible to see that the page contains printing. It is thought that such lenses should have value in saving life, where it is necessary to dive for a victim of drowning. Lifeguards now have largely to grope for the victim, and if he is entangled in brush, wreckage, etc., the lifeguard must depend largely on sense of touch. Precious moments thus lost result fatally for the victim.

In designing suitable lenses, it should be noted that ordinary glass has an index of refraction much nearer to water than to air, so that a single lens would be quite thick (unless made with highly refracting flint glass). The equivalent of an air lens in water may be constructed with two watch glasses having their convex surfaces facing each other, and the intermediate space kept dry by suitable mounting in a frame. This combination is rather fragile, and also subject to considerable refraction errors, although having the advantage that a person wearing it is able to see tolerably well *either in water or in air.* With the particular watch-glass lens constructed, it was difficult to read news print.

More rugged construction was possible with a pair of plano-convex lenses of index of refraction 1.523, with curvatures corresponding to 6 and 20 diopters, respectively. The lenses were arranged with their curved surfaces adjacent, and with the lens of greater curvature nearest the eye. This combination gave excellent underwater vision, being used as a hand lens for one eye at a time. Naturally the system is sealed, keeping the space between the lenses dry. Where the water is muddy as in certain swimming pools or harbors, vision may be limited to one or two meters, but in clear lakes one may see for a distance of very many meters.

SUMMARY

It is found that suitably designed lenses make possible excellent underwater vision for the otherwise naked eye.

INDEX TO VOLUME 23

("A" designates abstract of paper presented before the Optical Society.)

A

Aberration, axial chromatic, in an objective lens, method of measuring (W. Herriott), 123.
Aberrations of the concave grating at large angles of incidence (I. S. Bowen), 313
After-images, brightness of the stimulus and the duration of the stimulation as factors in the production of the "flight of colors" in the (William Berry), 119-A
Alkaline earth tungstates containing lead, luminescence of (Frank E. Swindells), 129
Alkaloids, infrared absorption spectra of certain (Sister Michael Edward O'Byrne), 92.
Alpha-rays, response of a photographic emulsion to (T. R. Wilkins and R. N. Wolfe), 324.
American Physical Society, joint session of the, and the Optical Society of America, 190.
American Secretariat Reports at 1931 meetings of the International Commission on Illumination, 149.
Amplification of galvanometer currents, photo-relay for the (Paul R. Gleason), 193-A.
Analytic color-tone chart (Rogers D. Rusk), 182.
Anisotropy, on the optical, of molecular crystals. I. Experimental (S. B. Hendricks and M. E. Jefferson), 299.
Annual report of Secretary, O.S.A. for 1932, 224.
Annual report of Treasurer, O.S.A. for 1932, 226.
Arcs, mercury, line intensity and energy distribution in high and low-pressure (L. B. Johnson and L. Burns), 55.
Associate to regular membership, transfer from, 116.
Astigmatism, on the, of the concave grating (G. H. Dieke), 274.
Astronomy and spectroscopy, photographic plates for use in (C. E. K. Mees), 192-A.
Axial chromatic aberration, method of measuring, in an objective lens (William Herriott), 117-A, 123.

B

BALINKIN, ISAY AND D. W. WELLS: Spectra of potassium and sodium in the mercury arc, 105.
BARNES, B. T. AND W. E. FORSYTHE: Large double crystalline quartz monochromator, 117-A.
——— W. E. FORSYTHE AND M. A. EASLEY: Ultraviolet radiation from some selected sources, 193-A.
BERRY, WILLIAM: Brightness of the stimulus and the duration of the stimulation as factors in the production of the "flight of colors" in the after-images, 119-A.
Biologically-effective radiation, fundamental units and terms for (M. Luckiesh and L. L. Holladay), 197.
BLAIR, JULIAN M. AND MALCOLM C. HYLAN: Intermittency effect in photographic exposure, 353.
——— AND KARL M. JOEHNCK: Herschel effect as a result of simultaneous forward and reverse reactions, 67.
BOWEN, I. S.: Aberrations of the concave grating at large angles of incidence, 313.
BOYLE, J. WATSON AND C. L. UTTERBACK: Light penetration in the waters of the San Juan Archipelago, 333.
Brightness of the stimulus and the duration of the stimulation as factors in the production of the "flight of colors" in the after-images (William Berry), 119-A.
BROOKER, L. G. S., F. M. HAMER AND C. E. K. MEES: Recent advances in sensitizers for the photography of the infrared, 216.
DE BRUIN, T. L. AND C. C. KIESS: First spark spectrum of chlorine and its structure, 121-A.
Bubble sextant at sea, experiments with the (E. O. Hulburt), 143.
BURNS, L. AND L. B. JOHNSON: Line intensity and energy distribution in high and low-pressure arcs, 55.
——— AND DONALD C. STOCKBARGER: Line shape as a function of the mode of spectrograph slit irradiation, 379.
BUTTERFIELD, J. V. AND L. V. FOSTER: Motion picture study of the behavior of the carbon arc, 121-A.
By-laws of the Optical Society of America, Inc., adoption of, 261.
By-laws, proposed, of the Optical Society of America, Inc., 151.
By-laws, revision of, 116.

C

Carbon arc, motion picture study of the behavior of the (L. V. Foster and J. V. Butterfield), 121-A.
Century of optics, session devoted to, 114.
Chemiluminescence, efficiency of, accompanying oxidation of Grignard compounds (Clarence Delmar Thomas and R. T. Dufford), 251
Chlorine, first spark spectrum of, and its structure (C. C. Kiess and T. L. de Bruin), 121-A.
Chromatic aberration, method of measuring axial in an objective lens (William Herriott), 117-A, 123.
Chromaticity of incandescent illuminants and various phases of daylight, proposed scale for use in specifying the (Irwin G. Priest), 41, 119-A.
Chromaticity sensibility to wave-length difference as a function of purity (E. P. T. Tyndall), 15.
Color blindness, total, description of a case of (Frank A. Geldard), 256
Color filters for altering color temperature. Pyrometer and Daylite glasses (H. P. Gage), 46, 119-A.
Colorimetric purity and relative brightness on the 1931 C. I. E. basis, computation from spectrophotometric data of trilinear coordinates, dominant wave-length (Deane B. Judd), 194-A.
Colorimetry committee, members of the, 190.
Colorimetry with reflection standards: A quasi-psychological method and data for the inter-conversion of physical and psychological color specifications (A. E. O. Munsell and I. H. Godlove), 194-A.
Color temperature and temperature of the magnesium flame in air, spectral energy distribution (Brian O'Brien and T. A. Russell), 118-A.
Color temperature change, sensibility to, as a function of temperature (Deane B. Judd), 7.
Color temperature, color filters for altering. Pyrometer and Daylite glasses (H. P. Gage), 46, 119-A.
Color temperature of tungsten-filament lamps as a function of time in service at constant voltage (Deane B. Judd), 118-A.
Color-tone chart, analytic (Rogers D. Rusk), 182.
Color vision in the house fly (Musca Domestica) (Zarmair Zakarian), 195-A.
Comparator, photoelectric, for precise and rapid measurement of reflection and transmission (C. H. Sharp and H. J. Eckweiler), 246
Concave grating, aberrations of the, at large angles of incidence (I. S. Bowen), 313.
Concave grating, on the astigmatism of the (G. H. Dieke), 274.
Concave grating spectrograph, focus of a (David L. MacAdam), 178.

Concave grating spectrograph, on the, especially at large angles of incidence: Addendum (J. E. Mack and J. R. Stehn), 184.
CONDON, E. U.: Modern theory of light (Title only), 114.
Coordinate system for colorimetry and 1931 I.C.I. standard observer (Deane B. Judd), 359.
CORNISH, ROBERT E.: Improving underwater vision of lifeguards and naked divers, 430.
Cosmic-ray electrons, lens for (W. F. G. Swann and W. E. Danforth, Jr.), 191-A.
Critical fusion frequency of intermittent illumination, influence of intensity on the, for different retinal locations and colors (Selig Hecht and C. D. Verrijp), 194-A.

D

DANFORTH, W. E., JR., AND W. F. G. SWANN: Lens for cosmic-ray electrons, 191-A.
DAVISSON, C. J.: Electron optics, 190-A.
Daylight, proposed scale for use in specifying the chromaticity of incandescent illuminants and various phases of (Irwin G. Priest), 41, 119-A.
Daylite glasses, pyrometer absorption and. Color filters for altering color temperature (H. P. Gage), 46, 119-A.
Deaths during the year (1931–1932), 114.
DEBYE, P. AND F. W. SEARS: Scattering of light by supersonic waves (Title only), 115.
DIEKE, G. H.: Astigmatism of the concave grating, 274.
Diffraction of low-speed electrons (H. E. Farnsworth), 191-A.
Directors of the Optical Society of America, Inc., minutes of the first meeting of the, 189.
Dominant wave-length, colorimetric purity and relative brightness on the 1931 C.I.E. basis, computation from spectrophotometric data of trilinear coordinates (Deane B. Judd), 194-A.
Double, large, crystalline quartz monochromator (W. E. Forsythe and B. T. Barnes), 117-A.
DUFFENDACK, O. S. AND K. B. THOMSON: Photographic method of measuring the relative intensities of spectral lines, 101.
DUFFORD, R. T. AND CLARENCE DELMAR THOMAS: Efficiency of the chemiluminescence accompanying oxidation of Grignard compounds, 251.
DURFEE, DOROTHY AND A. M. TAYLOR: Studies in refractive index. III, 263.

E

EASLEY, M. A., W. E. FORSYTHE AND B. T. BARNES: Ultraviolet radiation from some selected sources, 193-A.
ECKWEILER, H. J. AND C. H. SHARP: Photoelectric comparator for precise and rapid measurement of reflection and transmission, 246.
——— AND C. H. SHARP, S. McK. GRAY AND W. F. LITTLE: Photometry of solar eclipse phenomena, 192-A, 234.
Election of officers of Optical Society of America, Inc., notice of, 122.
Electromagnetic theory (Title only) (W. F. G. Swann), 114.
Electron beams in high vacuum (Vladimir K. Zworykin), 191-A.
Electron optics (C. J. Davisson), 190-A.
Electron optics, symposium on, 190.
Electrons, low-speed, diffraction of (H. E. Farnsworth), 191-A.
ELLIS JOSEPH W.: Some infrared interference spectra, 88.
Energy distribution, spectral, temperature and color temperature of the magnesium flame in air (Brian O'Brien and T. A. Russell), 118-A.
Entoptic and diffraction phenomena, observation of; new optical experiment and the use of a single lens for high magnification (J. Gibson Winans), 289.
ERIKSON, HENRY A.: Light intensity at different depths in lake water, 170.
Erythemal ultraviolet radiation, measurement of (A. H. Taylor), 60, 121-A.
Executive Council, minutes of the, 115.
Experiments with the bubble sextant at sea (E. O. Hulburt), 143.

F

FARNSWORTH, H. E.: Diffraction of low-speed electrons, 191-A.
FASSIN, GUSTAVE: Development of a microscope-centrifuge after Harvey-Loomis, 117-A.
———: New spark stand with rotatable electrodes, 193-A.
———: New type of spectrographic slit, 186, 193-A.
Films of sputtered tin, color in (C. J. Overbeck), 109.
Filters, color, for altering color temperature (pyrometer and Daylite glasses), (H. P. Gage), 119-A.
Financial statement of J.O.S.A.-R.S.I. for 1932, 223.
Focus of a concave grating spectrograph (David L. MacAdam), 178.
FORSYTHE, W. E.: Lantern slides for illustrating lectures, 117-A.
——— AND B. T. BARNES: Large double crystalline quartz monochromator, 117-A.
——— B. T. BARNES AND M. A. EASLEY: Ultraviolet radiation from some selected sources, 193-A.
FOSTER, L. V. AND J. V. BUTTERFIELD: Motion picture study of the behavior of the carbon arc, 121-A.
Fresnel and Young, sidelights on the era of (E. L. Nichols), 1.
FRY, THORNTON C. AND HERBERT E. IVES: Standing light waves: repetition of an experiment by Wiener, using a photoelectric probe surface, 73, 120-A.
Fundamental units and terms for biologically effective radiation (M. Luckiesh and L. L. Holladay), 197.

G

GAGE, H. P.: Color filters for altering color temperature. Pyrometer absorption and Daylite glasses, 46, 119-A.
GAMBLE, D. L. AND A. H. PFUND: Interference scheme for measuring the cell depth of a Siedentopf ultramicroscopic counting chamber, 416.
GARTLEIN, C. W. AND D. T. WILBER: Way of producing gratings giving Lyman ghosts, 193-A.
GELDARD, FRANK A.: Description of a case of total color blindness, 256.
GLEASON, PAUL R.: Photo-relay for the amplification of galvanometer currents, 193-A.
GLOVER, A. M. AND A. M. TAYLOR: Studies in refractive index, I and II, 206.
GODLOVE, I. H.: Neutral value scales. II. A comparison of results and equations describing value scales, 419.
——— AND A. E. O. MUNSELL: Colorimetry with reflection standards: A quasi-psychological method and data for the inter-conversion of physical and psychological color specifications, 194-A.
——— A. E. O. MUNSELL AND L. L. SLOAN: Neutral value scales. I. Munsell neutral value scale, 394.
GOLDMAN, STANFORD: Relation between the resolving power of a spectroscope and the principle of uncertainty, 70.
Gratings, way of producing, giving Lyman ghosts (D. T. Wilber and C. W. Gartlein), 193-A.
GRAY, S. MCK., C. H. SHARP, W. F. LITTLE, H. J. ECKWEILER: Photometry of solar eclipse phenomena, 192-A, 234.
Grignard compounds, efficiency of the chemiluminescence accompanying oxidation of (Clarence Delmar Thomas and R. T. Dufford), 251.

H

Hafnium lines, Zeeman effect on (William F. Meggers and Bourdon F. Scribner), 121-A.
HALL, CLYDE H. AND GEORGE S. HASLAM: Microscopic study of pigments with ultraviolet light, 195-A.

HAMER, F. M., L. G. S. BROOKER AND C. E. K. MEES: Recent advances in sensitizers for the photography of the infrared, 216.
HASLAM, GEORGE S. AND CLYDE H. HALL: Microscopic study of pigments with ultraviolet light, 195-A.
HECHT, SELIG AND CORNELIUS D. VERRIJP: Influence of intensity on the critical fusion frequency of intermittent illumination for different retinal locations and colors, 194-A.
HENDRICKS, S. B. AND M. E. JEFFERSON: Optical anisotropy of molecular crystals. I. Experimental, 299.
HERRIOTT, WILLIAM: Method of measuring axial chromatic aberration in an objective lens, 117-A, 123.
Herschel effect as a result of simultaneous forward and reverse reactions (Karl M. Joehnck and Julian M. Blair), 67
HODGMAN, CHARLES D.: Transmission of ultraviolet radiation by water, 426.
HOLLADAY, L. L. AND M. LUCKIESH: Fundamental units and terms for biologically-effective radiation, 197
House fly, color vision in the (Musca Domestica) (Zarmair Zakarian), 195-A.
HULBURT, E. O.: Experiments with the bubble sextant at sea, 143.
Hydrogen effect in certain oxides (E. L. Nichols and C. L. Stanford), 120-A.
HYLAN, MALCOLM AND JULIAN M. BLAIR: Intermittency effect in photographic exposure, 353.

I

Incandescent illuminants and various phases of daylight, proposed scale for use in specifying the chromaticity of (Irwin G. Priest), 41, 119-A.
Infrared absorption spectra of certain alkaloids (Sister Michael Edward O'Byrne), 92.
Infrared interference spectra, some (Joseph W. Ellis), 88.
Infrared radiation from small particles (A. H. Pfund), 270.
Infrared, recent advances in sensitizers for the photography of the (L. G. S. Brooker, F. M. Hamer and C. E. K. Mees), 216.
Intensities of spectral lines, photographic method of measuring the relative (K. B. Thomson and O. S. Duffendack), 101.
Intensity and spectral distribution of solar radiation in New Orleans (Henry Laurens and H. S. Mayerson), 133.
Interference of light in metallic films (J. B. Nathanson), 388.
Interference spectra, some infrared (Joseph W. Ellis), 88.
Interferometer, triple, for distinguishing flexural and longitudinal vibrations in quartz (H. Osterberg), 30.
Intermittency effect and the reciprocity law failure in photographic exposure (J. H. Webb), 192-A.
Intermittency effect in photographic exposure (Julian M. Blair and Malcolm C. Hylan), 353.
Intermittency effect in photographic exposure, relationship between reciprocity law failure and the (J. H. Webb), 157.
International commission on illumination, American Secretariat reports at the 1931 meetings of the, 149.
IVES, HERBERT E. AND THORNTON C. FRY: Standing light waves; Repetition of an experiment by Wiener, using a photoelectric probe surface, 73, 120-A.
Ives Medal Committee for 1933, 190.
Ives Medal to be awarded in 1933, 116.

J

JEFFERSON, M. E. AND S. B. HENDRICKS: Optical anisotropy of molecular crystals. I. Experimental, 299.
JOEHNCK, KARL M. AND JULIAN M. BLAIR: Herschel effect as a result of simultaneous forward and reverse reactions, 67.
JOHNSON, L. B. AND L. BURNS: Line intensity and energy distribution in high and low-pressure mercury arcs, 55.
JUDD, DEANE B.: Color temperature of tungsten-filament lamps as a function of time in service at constant voltage, 118-A.
———: Computation from spectrophotometric data of trilinear coordinates, dominant wave-length, colorimetric purity and relative brightness on the 1931 C.I.E. basis, 194-A.
———: 1931 I.C.I. standard observer and coordinate system for colorimetry, 359.
———: Saturation scale for yellow colors, 35.
———: Sensibility to color-temperature change as a function of temperature, 7.

K

KIESS, C. C. AND T. L. DE BRUIN: First spark spectrum of chlorine and its structure, 121-A.
KING, ALLEN AND A. M. TAYLOR: Studies in refractive index. Part IV, 308.
KINGSLAKE, R. AND A. B. SIMMONS: Method of projecting star images having coma and astigmatism, 282.

L

Lake Placid Club, vote of thanks to, 115.
Lake water, light intensity at different depths in (Henry A. Erikson), 170.
Lantern slides for illustrating lectures (W. E. Forsythe), 117-A.
Latent (photographic) image, time lag in the formation of the (Lester I. Zimmerman), 342.
LAURENS, HENRY AND H. S. MAYERSON: Intensity and spectral distribution of solar radiation in New Orleans, 133.
Lens for cosmic-ray electrons (W. F. G. Swann and W. E. Danforth, Jr.), 191-A.
Lens, method of measuring axial chromatic aberration in an objective (William Herriott), 117-A, 123.
Light intensity at different depths in lake water (Henry A. Erikson), 170
Light penetration in the waters of the San Juan Archipelago (C. L. Utterback and J. Watson Boyle), 333.
Light penetration in the waters of Southern Alaska (C. L. Utterback), 339.
Line intensity and energy distribution in high and low-pressure mercury arcs (L. B. Johnson and L. Burns), 55.
Line shape as a function of the mode of spectrograph slit irradiation (D. C. Stockbarger and Laurence Burns), 379.
LITTLE, W. F., C. H. SHARP, S. MCK. GRAY, H. J. ECKWEILER: Photometry of solar eclipse phenomena, 192-A, 234.
Low-speed electrons, diffraction of (H. E. Farnsworth), 191-A.
LUCKIESH, M. AND L. L. HOLLADAY: Fundamental units and terms for biologically-effective radiation, 197.
——— AND FRANK K. MOSS: Dependency of visual acuity upon stimulus-distance, 25.
——— AND FRANK K. MOSS: Visual acuity as a function of stimulus distance, 120-A.
Luminescence of alkaline earth tungstates containing lead (Frank E. Swindells), 129.
Lyman ghosts, way of producing gratings giving (D. T. Wilber and C. W. Gartlein), 193-A.

M

MACADAM, DAVID L.: Focus of a concave grating spectrograph, 178.
MACK, J. E. AND J. R. STEHN: Concave grating spectrograph, especially at large angles of incidence: Addendum, 184.
Magnesium flame in aid, spectral energy distribution, temperature and color temperature of the (Brian O'Brien and T. A. Russell), 118-A.

MAYERSON, H. S. AND HENRY LAURENS: Intensity and spectral distribution of solar radiation in New Orleans, 133.
Measurement of erythemal ultraviolet radiation (A. H. Taylor), 60, 121-A.
MEES, C. E. KENNETH: Photographic plates for use in spectroscopy and astronomy. III, 192-A, 229.
——— L. G. S. BROOKER AND F. M. HAMER: Recent advances in sensitizers for the photography of the infrared, 216.
Meeting of the Optical Society of America, Lake Placid Club, New York, October 13–15, 1932, proceedings of the seventeenth annual, 114.
MEGGERS, WILLIAM F. AND BOURDON F. SCRIBNER: Zeeman effect on hafnium lines, 121-A.
Mercury arc, spectra of potassium and sodium in the (D. A. Wells and Isay Balinkin), 105.
Mercury arcs, line intensity and energy distribution in high and low-pressure (L. B. Johnson and L. Burns), 55.
Metallic films, interference of light in (J. B. Nathanson), 388.
Microscope-centrifuge, development of a, after Harvey-Loomis (Gustave Fassin), 117-A.
Microscopic study of pigments with ultraviolet light (George S. Haslam and Clyde H. Hall), 195-A.
Minutes of the executive council, October 13 and 14, 1932, 115.
Minutes of the first meeting of the Optical Society of America, Inc., 189.
Modern theory of light (Title only) (E. U. Condon), 114.
MOHLER, F. L.: Experimental evidence for the absence of scattering of light by light, 386.
Molecular crystals, on the optical anisotropy of. I. Experimental (S. B. Hendricks and M. E. Jefferson), 299.
Monochromator, large double crystalline quartz (W. E. Forsythe and B. T. Barnes), 117-A.
MOSS, FRANK K. AND M. LUCKIESH: Dependency of visual acuity upon stimulus-distance, 25.
——— AND M. LUCKIESH: Visual acuity as a function of stimulus distance, 120-A.
Motion picture study of the behavior of the carbon arc (L. V. Foster and J. V. Butterfield), 121-A.
Multiple prism glass spectrograph (D. H. Rank), 84
MUNSELL, A. E. O. AND I. H. GODLOVE: Colorimetry with reflection standards: A quasi-psychological method and data for the inter-conversion of physical and psychological color specifications, 194-A.
——— L. L. SLOAN AND I. H. GODLOVE: Neutral value scales. I. Munsell neutral value scale, 394.
Munsell neutral value scale (A. E. O. Munsell, L. L. Sloan and I. H. Godlove), 394.

N

NATHANSON, J. B.: Interference of light in metallic films, 388.
Neutral value scales. I. Munsell neutral scale (A. E. O. Munsell, L. L. Sloan and I. H. Godlove), 394.
Neutral value scales. II. A comparison of results and equations describing value scales (I. H. Godlove), 419.
New optical experiment and the use of a single lens for high magnification; observation of entoptic and diffraction phenomena (J. Gibson Winans), 289.
NICHOLS, E. L.: Sidelights on the era of Young and Fresnel, 1.
——— AND C. L. STANFORD: Hydrogen effect in certain oxides, 120-A.
Nominating committee for the regular election in October, 1933, 190.

O

O'BRIEN, BRIAN AND T. A. RUSSELL: Spectral energy distribution, temperature and color temperature of the magnesium flame in air, 118-A.
O'BYRNE, SISTER MICHAEL EDWARD: Infrared absorption spectra of certain alkaloids, 92.
Officers for the Optical Society of America, Inc., notice of election of, 122.
Optical, on the anisotropy of molecular crystals. I. Experimental (S. B. Hendricks and M. E. Jefferson), 299.
Optical properties of metallic and crystalline powders (A. H. Pfund), 375.
Optical Society of America, Inc., adoption of by-laws of the, 261.
Optical Society, proceedings of the New York meeting, February 24–25, 1933, 189.
Optical Society, proceedings of the Seventeenth annual meeting of, Lake Placid Club, New York, October 13–15, 1932, 114.
Optical Society, proposed by-laws of the, 151.
Optical Society, report of the business manager, 223.
Optical Society, report of the secretary, 224.
Optical Society, report of the treasurer, 226.
Optical tests of the 69-inch Perkins observatory reflector (Harlan T. Stetson), 293.
OSTERBERG, H.: Triple interferometer for distinguishing flexural and longitudinal vibrations in quartz, 30.
OVERBECK, CLARENCE J.: Color in films of sputtered tin, 109.
Oxides, hydrogen effect in certain (E. L. Nichols and C. L. Stanford), 120-A.

P

Perkins observatory reflector, optical tests of the 69-inch (Harlan T. Stetson), 293.
PFUND, A. H.: Infrared radiations from small particles, 270.
———: Optical properties of metallic and crystalline powders, 375.
——— AND D. L. GAMBLE: Interference scheme for measuring the cell depth of a Siedentopf ultramicroscopic counting chamber, 416.
Photoelectric comparator for precise and rapid measurement of reflection and transmission (Clayton H. Sharp and H. J. Eckweiler), 246.
Photographic emulsion, response of a, to alpha-rays (T. R. Wilkins and R. N. Wolfe), 324.
Photographic exposure, intermittency effect and the reciprocity law failure in (J. H. Webb), 192-A.
Photographic exposure, intermittency effect in (Julian M. Blair and Malcolm C. Hylan), 353.
Photographic exposure, relationship between reciprocity law failure and the intermittency effect in (J. H. Webb), 157.
Photographic method of measuring the relative intensities of spectral lines (K. B. Thomson and O. S. Duffendack), 101.
Photographic plates for use in spectroscopy and astronomy. III (C. E. K. Mees), 192-A, 229.
Photographic reciprocity law failure for radiation of different wave-length (J. H. Webb), 316.
Photography of the infrared, recent advances in sensitizers for the (L. G. S. Brooker, F. M. Hamer and C. E. K. Mees), 216.
Photometry of solar eclipse phenomena (Clayton H. Sharp, S. McK. Gray, W. F. Little, H. J. Eckweiler), 192-A, 234.
Photo-relay for the amplification of galvanometer currents (Paul R. Gleason), 193-A.
Physical optics, contributed papers on, 120.
Pigments, microscopic study of, with ultraviolet light (George S. Haslam and Clyde H. Hall), 195-A.
PINEO, O. W.: Modified Rochon prism, 117-A.
Potassium and sodium, spectra of, in the mercury arc (D. A. Wells and Isay Balinkin), 105.
Powders, optical properties of metallic and crystalline (A. H. Pfund), 375.
PRIEST, IRWIN G.: Proposed scale for use in specifying the chromaticity of incandescent illuminants and various phases of daylight, 41, 119-A.

Principle of uncertainty, relation between the resolving power of a spectroscope and the (Stanford Goldman), 70.
Proceedings of the Optical Society of America, New York meeting, February 24–25, 1933, 189.
Proceedings of the Seventeenth annual meeting of the Optical Society of America, Lake Placid Club, New York, October 13–15, 1932, 114.
Projecting star images having coma and astigmatism, method of (R. Kingslake and A. B. Simmons), 282.
(Proposed) by-laws of the Optical Society of America, Inc., 151.
Pyrometer absorption and Daylite glasses. Color filters for altering color temperature (H. P. Gage), 46, 119-A.

Q

Quartz monochromator, large double crystalline (W. E. Forsythe and B. T. Barnes), 117-A.
Quartz, triple interferometer for distinguishing flexural and longitudinal vibrations in (H. Osterberg), 30.

R

RANK, D. H.: Multiple prism glass spectrograph, 84.
Reciprocity law failure, and the intermittency effect in photographic exposure, relationship between (J. H. Webb), 157, 192-A.
Reciprocity law failure, photographic, for radiations of different wave-length (J. H. Webb), 316.
Reflection and transmission, photoelectric comparator for precise and rapid measurement of (Clayton H. Sharp and H. J. Eckweiler), 246.
Reflection standards, colorimetry with: A quasi-psychological method and data for the inter-conversion of physical and psychological color specifications (A. E. O. Munsell and I. H. Godlove), 194-A.
Reflector, optical tests of the 69-inch Perkins observatory (Harlan T. Stetson), 293.
Refractive index, studies in, I and II (A. M. Taylor and A. M. Glover), 206.
Refractive index, studies in, III. (A. M. Taylor and Dorothy A. Durfee), 263.
Refractive index, studies in, Part IV (A. M. Taylor and Allen King), 308
Relative brightness on the 1931 C.I.E. basis, computation from spectrophotometric data of trilinear coordinates, dominant wave-length, colorimetric purity and (Deane B. Judd), 194-A.
Resolving power of a spectroscope, relation between, and the principle of uncertainty (Stanford Goldman), 70.
Rochon prism, modified (O. W. Pineo), 117-A.
Rotatable electrodes, new spark stand with (Gustave Fassin), 193-A.
RUSK, ROGERS D.: Analytic color-tone chart, 182.
RUSSELL, T. A. AND BRIAN O'BRIEN: Spectral energy distribution, temperature and color temperature of the magnesium flame in air, 118-A.

S

San Juan Archipelago, light penetration in the waters of the (C. L. Utterback and J. Watson Boyle), 333.
Saturation scale for yellow colors (Deane B. Judd), 35.
Scale, proposed, for use in specifying the chromaticity of incandescent illuminants and various phases of daylight (Irwin G. Priest), 41, 119-A.
Scattering of light by light, experimental evidence for the absence of (F. L. Mohler), 386.
Scattering of light by supersonic waves (Title only) (F. W. Sears and P. Debye), 115.
SCRIBNER, BOURDON F. AND WILLIAM F. MEGGERS: Zeeman effect on hafnium lines, 121-A.
SEARS, F. W. AND P. DEBYE: Scattering of light by supersonic waves (Title only), 115.
Secretariat reports, American, at 1931 meetings of the International Commission on Illumination, 149.
Secretary, O. S. A., annual report of, for 1932, 224.
Sensibility, chromaticity, to wave-length difference as a function of purity (E. P. T. Tyndall), 15.
Sensibility to color-temperature change as a function of temperature (Deane B. Judd), 7.
Sensitizers for the photography of the infrared, recent advances in (L. G. S. Brooker, F. M. Hamer and C. E. K. Mees), 216.
Sextant, bubble, at sea, experiments with the (E. O. Hulburt), 143.
SHARP, CLAYTON H. AND H. J. ECKWEILER: Photoelectric comparator for precise and rapid measurement of reflection and transmission, 246.
——— S. MCK. GRAY, W. F. LITTLE, H. J. ECKWEILER: Photometry of solar eclipse phenomena, 192-A, 234.
Siedentopf ultra-microscopic counting chamber, interference scheme for measuring the cell depth of a (D. L. Gamble and A. H. Pfund), 416.
SIMMONS, A. B. AND R. KINGSLAKE: Method of projecting star images having coma and astigmatism, 282.
Slit, new type of spectrographic (Gustave Fassin), 186, 193-A.
SLOAN, L. L., A. E. O. MUNSELL, AND I. H. GODLOVE: Neutral value scales. I. Munsell neutral value scale, 394.
Small particles, infrared radiations from (A. H. Pfund), 270.
Sodium, spectra of potassium and, in the mercury arc (D. A. Wells and Isay Balinkin), 105.
Solar eclipse phenomena, photometry of (Clayton H. Sharp, S. McK. Gray, W. F. Little, H. J. Eckweiler), 192-A, 234.
Solar radiation in New Orleans, intensity and spectral distribution of (Henry Laurens and H. S. Mayerson), 133.
Southern Alaska, light penetration in the waters of (C. L. Utterback), 339.
Spark spectrum, first, of chlorine and its structure (C. C. Kiess and R. L. de Bruin), 121-A.
Spark stand, new, with rotatable electrodes (Gustave Fassin), 193-A.
Spectra of potassium and sodium in the mercury arc (D. A. Wells and Isay Balinkin), 105.
Spectral and intensity distribution of solar radiation in New Orleans (Henry Laurens and H. S. Mayerson), 133.
Spectral energy distribution, temperature and color temperature of the magnesium flame in air (Brian O'Brien and T. A. Russell), 118-A.
Spectral lines, photographic method of measuring the relative intensities of (K. B. Thomson and O. S. Duffendack), 101.
Spectrograph, focus of a concave grating (David L. MacAdam), 178.
Spectrograph, multiple prism glass (D. H. Rank), 84.
Spectrograph, on the concave grating, especially at large angles of incidence: Addendum (J. E. Mack and J. R. Stehn), 184.
Spectrograph slit irradiation, line shape as a function of the mode of (Donald C. Stockbarger and Laurence Burns), 379.
Spectrographic slit, new type of (Gustave Fassin), 186, 193-A.
Spectrophotometric data of trilinear coordinates, dominant wave-length, colorimetric purity and relative brightness on the 1931 C.I.E. basis, computation from (Deane B. Judd), 194-A.
Spectroscopy and astronomy, photographic plates for use in. III. (C. E. Kenneth Mees), 192-A, 229.
Sputtered tin, color in films of (Clarence J. Overbeck), 109.
Standard observer, 1931 I.C.I., and coordinate system for colorimetry (Deane B. Judd), 359.
Standing light waves; repetition of an experiment by Wiener, using a photoelectric probe surface (Herbert E. Ives and Thornton C. Fry), 73, 120-A.

STANFORD, C. L. AND E. L. NICHOLS: Hydrogen effect in certain oxides, 120-A.
Star images having coma and astigmatism, method of projecting (R. Kingslake and A. B. Simmons), 282.
STEHN, J. R. AND J. E. MACK: Concave grating spectrograph, especially at large angles of incidence. Addendum, 184.
STETSON, HARLAN T.: Official tests of the 69-inch Perkins observatory reflector, 293.
Stimulus, brightness of the, and the duration of the stimulation as factors in the production of the "flight of colors" in the after-images (William Berry), 119-A.
Stimulus-distance, dependency of visual acuity upon (M. Luckiesh and Frank K. Moss), 25, 120-A.
STOCKBARGER, DONALD C. AND LAURENCE BURNS: Line shape as a function of the mode of spectrograph slit irradiation, 379.
Supersonic waves, scattering of light by (Title only) (F. W. Sears and P. Debye), 115.
SWANN, W. F. G.: Electromagnetic theory (Title only), 114.
——— AND M. E. DANFORTH, JR.: Lens for cosmic-ray electrons, 191-A.
SWINDELLS, FRANK E.: Luminescence of alkaline earth tungstates containing lead, 129.

T

TAYLOR, A. H.: Measurement of erythemal ultraviolet radiation, 60, 121-A.
——— AND DOROTHY A. DURFEE: Studies in refractive index. III, 263.
——— AND A. M. GLOVER: Studies in refractive index, I and II, 206.
——— AND ALLEN KING: Studies in refractive index. Part IV, 308.
Temperature and color temperature of the magnesium flame in air, spectral energy distribution (Brian O'Brien and T. A. Russell), 118-A.
THOMAS, CLARENCE DELMAR AND R. T. DUFFORD: Efficiency of the chemiluminescence accompanying oxidation of Grignard compounds, 251.
THOMSON, K. B. AND O. S. DUFFENDACK: Photographic method of measuring the relative intensities of spectral lines, 101.
Time lag in the formation of the latent (photographic) image (Lester I. Zimmerman), 342.
Tin, sputtered, color in films of (Clarence J. Overbeck), 109.
Total color blindness, description of a case of (F. A. Geldard), 256.
Transfers from associate to regular membership, 116.
Transmission and reflection, photoelectric comparator for precise and rapid measurement of (Clayton H. Sharp, and H. J. Eckweiler), 246.
Transmission of ultraviolet radiation by water (Charles D. Hodgman), 426.
Treasurer O. S. A., annual report of, for 1932, 226.
Trilinear coordinates, computation from spectrophotometric data of, dominant wave-length, colorimetric purity and relative brightness on the 1931 C.I.E. basis (Deane B. Judd), 194-A.
Tungstates, alkaline earth, containing lead, luminescence of (Frank E. Swindells), 129.
Tungsten-filament lamps, color temperature of, as a function of time in service at constant voltage (Deane B. Judd), 118-A.
TYNDALL, E. P. T.: Chromaticity sensibility to wave-length difference as a function of purity, 15.

U

Ultraviolet light, microscopic study of pigments with (George S. Haslam and Clyde H. Hall), 195-A.
Ultraviolet radiation, erythemal, measurement of (A. H. Taylor), 55, 121-A.
Ultraviolet radiation from some selected sources (W. E. Forsythe, B. T. Barnes and M. A. Easley), 193-A.
Ultraviolet radiation, transmission of, by water (Charles D. Hodgman), 426.
Underwater vision of lifeguards and naked divers, improving (Robert E. Cornish), 430.
UTTERBACK, C. L.: Light penetration in the waters of Southern Alaska, 339.
——— AND J. WATSON BOYLE: Light penetration in the waters of the San Juan Archipelago, 333.

V

VERRIJP, C. D. AND SELIG HECHT: Influence of intensity on the critical fusion frequency of intermittent illumination for different retinal locations and colors, 194-A.
Vision, improving underwater, of lifeguards and naked divers (Robert E. Cornish), 430.
Visual acuity, dependency of upon stimulus-distance (M. Luckiesh and Frank K. Moss), 25, 120-A.
Visual optics, contributed papers on, 118.

W

WEBB, J. H.: Intermittency effect and the reciprocity law failure in photographic exposure, 192-A.
———: Photographic reciprocity law failure for radiations of different wave-length, 316.
———: Relationship between reciprocity law failure and the intermittency effect in photographic exposure, 157
WELLS, D. A. AND ISAY BALINKIN: Spectra of potassium and sodium in the mercury arc, 105.
Wiener, repetition of an experiment by, using a photoelectric probe surface; standing light waves (Herbert E. Ives and Thornton C. Fry), 73, 120-A.
WILBER, D. T. AND C. W. GARTLEIN: Way of producing gratings giving Lyman ghosts, 193-A.
WILKINS, T. R. AND R. N. WOLFE: Response of a photographic emulsion to alpha-rays, 324.
WINANS, J. GIBSON: New optical experiment and the use of a single lens for high magnification; observation of entoptic and diffraction phenomena, 289.
WOLFE, R. N. AND T. R. WILKINS: Response of a photographic emulsion to alpha-rays, 324.
Wood, Robert Williams, Ives medallist for 1933, 413.

Y

Yellow colors, saturation scale for (Deane B. Judd), 35.
Young and Fresnel, sidelights on the era of (E. L. Nichols), 1.

Z

ZAKARIAN, ZARMAIR: Color vision in the house fly (Musca Domestica), 195-A.
Zeeman effect on hafnium lines (W. F. Meggers, and B. F. Scribner), 121-A.
ZIMMERMAN, LESTER I.: Time lag in the formation of the latent (photographic) image, 342.
ZWORYKIN, VLADIMIR K.: Electron beams in high vacuum, 191-A.